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THE ROLE OF TESTING IN THE ENGINEERING PRODUCT DEVELOPMENT PROCESS

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ABSTRACT

Testing is essential in developing a successful complex engineering product. System level integration and testing can use between 25 and 50% of development resources. External factors such as legislation and customer requirements drive essential testing whilst internal factors such company experience, affordability and organizational practice frame the overall testing plan. The main objective of this paper is to understand how testing is integrated into the product development process and how different types of testing are scheduled across the stages of product development. The paper reports a case study in a diesel engine company where the balance of virtual and physical testing is a key concern in reducing design time and costs. The importance of dependencies across components, subsystems and tests is highlighted and a model using Design Structure Matrices is proposed. Of particular interest are requirements analysis and FMEA stages where testing is planned and resourced. Integrating physical and virtual testing is more than process optimization of time and cost. It contributes to recasting the design process in response to change, both in new customer requirements and contingently in design changes which arise during product development.

KEYWORDS

Testing, physical testing, virtual testing, analysis, product development process, engineering design

1. INTRODUCTION

In competitive markets performance, reliability, safety and durability are critical for the success of engineered products. Testing is a necessary activity for verifying and validating the functionality, durability or reliability of a product. A potential design can be subject to mismatches with customer needs, technical design faults, or issues regarding manufacturability and maintainability of the product [1, 2]. Testing is a primary way to identify these problems and therefore is central to product development (PD) [3, 4]. But testing is an expensive and time consuming process. A critical aspect of the design process is to effectively deploy various testing activities throughout the PD process to assure product quality. This research will seek to understand the role of testing in different stages of the PD process.

In the PD cycle, from the early verification of the design to the final testing, designs are continually tested both virtually and physically. The power and scope of computational modelling means that virtual testing can deal with multiple variables, such as environmental factors or variations in manufacturing. The outcomes of such analyses give the basis for optimizing the use and design of costly physical testing which may be necessary for validation and certification. So, one key concern is how to best select various physical and virtual testing activities during the PD cycle.

Companies test products at several levels; system level, subsystem level and component level. Although sometimes system level tests are

minimized due to the pressure of time and cost at the end of project, experts suggest system level testing should be detailed and complete [5] as some problems only emerge at system level. Reducing subsystem level testing is a less risky way of making cost savings, since problems can be found later during the system level testing. Cutting the system level testing runs the risk of finding mistakes even later when the product is in use [5]. Although finding a problem at a system level may require costly redesign a problem in use is even more expensive for the business.

The cost of redesign or design changes increases through the PD process and late changes can have serious consequences on costs [6]. However, as the pressure increases to reduce the time to market, companies tend to be anxious to freeze the design changes to accelerate the testing process. Testing and design tasks are often performed in parallel and are iterative. Thus scheduling of tests across the product design and development process to maximize the benefit gained from tests is fundamental issue.

Two specific research questions were posed in this investigation.

1. What factors drive or influence the choice of a type of testing?
2. What are the appropriate modes or combination of tests in different stages of the PD process?

Dependency Structure Matrices (DSM), an established method for capturing the sequence and complex interaction of design tasks [7], are used to visualize the interdependency between tests and between components and tests.

In this research we considered three contrasting areas of Product Development: (i) early design including requirements analysis and conceptual modelling, (ii) detailed product development and (iii) engineering changes, which can occur throughout the entire process. In Section 2 the background and context are described with reference to the literature. Section 3 describes the methodology. Section 4 discusses a case study with a complex engineering product. Section 4.1 focuses on specific factors and competitiveness in the market. Section 4.2 details the decisions on type and comparative analysis between virtual and physical mode of testing and section 4.3 illustrates the current testing practice of Case Study Company. In section 5 we propose a Design Structure Matrix (DSM) model for dependencies across testing and components. Finally, in section 6 we conclude that

creating an effective testing plan, especially in managing engineering change depends critically on (i) relation between design and test processes, (ii) trade-offs between physical and virtual tests and (iii) dependencies between tests.

2. BACKGROUND AND CONTEXT

Many hundreds of tests are required during the PD cycle but little analytical effort has been given to effectively plan the testing through the PD process. In fact, there is little in the literature related to testing as part of the PD process. Most of the literature describes testing techniques. Some papers allude to testing in the context of general product development and briefly outline its relevance [1, 8-11].

Testing does not receive the same attention as other activities in the PD process. As testing has a tendency to be performed at the end of the PD process it is not necessarily viewed as an integral part of the whole PD process. Although many companies use tools such as Quality Function Development (QFD), Failure Modes and Effect Analysis (FMEA) to focus on product requirements that require testing in the early stages of PD [12], it is often the case that the testing is not fully planned until the design is well underway [13] or be static and not always reflect ongoing changes in design. A systematic treatment of test in the context of design and product development is limited and this paper attempts to fill this gap.

Testing is clearly linked to validation and verification in the literature. For example, the European Cooperation on Space Standardization (ECSS) secretariat documented that "*Testing is a method of verification. The verification is executed by one or more of the following methods: test, analysis, review of design and inspection*" [14]. Hoppe states, "*testing can be viewed as a subset of verification and validation*" [10].

The cost of conducting a test involves the cost of using the equipment, materials, facilities, staff and other engineering resources. Testing costs can be significantly higher than other expenditures in R&D. Typically the cost of testing can consume up to 50% of total development cost. In the spacecraft industry, system level integration and testing (I&T) alone costs approximately 35-50% of total development resources [15]. In the software industry testing can consume fifty percent or more of the development costs [16].

To reduce the increasing cost and time of testing, there is an industrial shift towards virtual testing. Options include computer aided testing (CAT) and Finite Element Analysis (FEA), for example. These types of technique are used to predict a product's behaviour. Advanced computing facilities improve the speed and economics of this virtual testing process. However, the acceptance of virtual testing is still debated in industry. This is because virtual tests should replicate a product's physical behaviour to provide confidence in the virtual tests. Moreover physical testing is a necessary industrial practice, usually required for product certification. For example, aerospace industries undertake a rigorous testing regime to pass certification criteria and automobile manufacturers test their prototypes for regulatory and safety standards [17].

Despite the fact of frequent changes in product characteristics and working conditions, companies continue to use the same test beds and facilities. They might perform a test or repeat a test which brings little new insight. They rely on highly subjective decision factors and sometimes it is doubtful if the rationale for the tests remains valid in new products. Britton [13] noted that one engineer in NASA stated, *"not enough emphasis is placed early enough on high-quality test requirements, equipment, and procedures. We make it work but it is not efficient"* [13]. However some tests may be difficult to alter due to the risk associated with failure of the component, especially when tests have resulted in producing successful components. For example helicopter rotors are critical elements for the safety and integrity of the aircraft and there is, understandably, some resistance to change testing processes.

A test plan is rarely a standardized process in product development. Planning and sequencing of tests in the PD process is self-adaptive and depends on the organizational culture and experience within the company [18]. Decisions are mostly based on the tacit knowledge of engineers.

In general testing is studied as a subsidiary step of the whole PD process. Design and analysis aspects of the PD drive testing tasks, through identifying product and component characteristics which require testing. Results from testing validate design decisions. The testing parts of PD processes have received less attention in the literature than the associated design or analysis tasks. As testing processes consume significant time and cost

resources and are a major milestone for product's success, testing is worthwhile to study as a PD process in its own right. Identifying the types and modes of testing and interrelations between the testing is significant for studying the testing process. However, the interrelations between the tests are not straightforward and often indirect because the product design and the testing process are intertwined. The analysis during the product design phase is a key input to the CAE analysis and simulation (i.e. virtual testing) and physical testing phases. Conversely virtual and physical testing can act as a critical input to design as well as providing essential validation. These information exchanges between design and test provide essential links in the product development process and identify how the testing processes can be integrated more closely with whole PD process. There is no supporting tool or model for identifying or connecting the testing activities along the PD process. The research study reported here integrates testing activities and their planning along the PD process.

3. METHODOLOGY

A case study methodology was employed in the first stage of this investigation. A major case study was undertaken at a UK based diesel engine manufacturing company. The company designs and manufactures diesel engines. Product changes are generally incremental. The diesel engine is a complex product with significant levels of testing. Many aspects including complexity of the product, safety criticality, pressure of legislation, high competitiveness make the testing for this product crucial. This company was chosen to demonstrate the criticality of testing and how testing is dealt with in a complex engineering field where legally imposed tests play a vital role.

Seven interviews were carried out over a ten months period from March 2011 to December 2011 building on a previous series of interviews on system architecture reported in [19]. We interviewed five engineers including a senior engineer, a development engineer, a CAE engineer, a verification & validation manager and a validation team leader. Interviews all took place at the company site.

The first interview with senior engineer gave us a general overview and an idea of expenditure around testing. It was mentioned that *"...to develop the Tier4 engines can cost R&D alone in excess of £X million, I would break it down to design and engineering is*

probably 15%, material is probably around 30%, and actually testing around performance is the rest at around 55%. So most of the money in R&D goes into testing for performance and durability". Shifting from physical testing to virtual testing (or a combinatorial approach with respect to design parameters) was highlighted as a key means of cost minimization. Then we interviewed a validation manager and the validation team leader to investigate how testing really happens on a component and system level. To investigate the relation between the verification and validation phase in product design we talked with development engineers in the presence of the validation team leader and the validation manager.

The authors were all present in each of these interviews. The interviews were recorded and transcribed. Each interview was approximately two and a half hours in length. The understanding and notes were shared and compared among the authors after each meeting in the company. The analysis of each interview raised several questions which drove the next interview. Sequential interviews were required to bring in a range of engineers, for wider understanding and for identifying the gaps in the current process.

We used a design/dependency structure matrix (DSM) to capture the dependencies and interrelationships of components and tests. As complex engines have hundreds of components and related tests, initially we modelled a small part of the engine. This included dependencies between components and interrelations between tests with the aim of understanding the organization of testing tasks. We went back to the engineers to corroborate the model and to discuss its effectiveness. The model helped us to visualise our understanding of the company's current practice and allowed the engineers to reflect on their practice.

4. TESTING IN INDUSTRIAL PRACTICE: A CASE STUDY

This section reports on the testing practice in the case study company. The structure of this section is as follows: in section 4.1, a discussion around product and market is presented. Internal factors such as product characteristics, architecture and newness in design have an influence on what is tested and how it is tested. External factors like legislation make some tests mandatory; and thereby determine or shift some of the testing practice in companies. Section 4.2

focuses more on types and mode of testing and comparative choice of testing and section 4.3 discusses the testing process across the whole product development process.

4.1. Product and market

The company mainly categorizes testing with respect to the three key product characteristics: reliability, durability and performance. Reliability tests ensure the ability to perform the specified operation without failing over a period of time. It is not feasible to look at reliability in each of the applications for which the product will be used as it is not economical to run thousands of hours of durability tests. Engineers therefore use statistical analysis to model the variability of the design specification and manufacturing capability [20, 21]. The durability of a product is highly dependent on how a product is used in the field. Understanding and analyzing the existing product's life cycle helps to predict the acceptable life of a new product. For performance, one senior engineer explained that, *"performance cannot be achieved only through simulation, we need to physically test"*.

New designs are created incrementally by adding new functionality or new properties to an existing product. Even if an existing component is deployed in a new context or to new requirements, it is considered "new" and therefore needs be retested [19]. Some changes propagate, which may have serious consequences resulting in the need for a step change in design. Incremental design changes can be managed with one kind of testing activity whereas step changes require a different kind of test plan. For example, if the company is designing a cylinder block which is a scaled version of a previous product, critically stressed areas would be already known thus it might be possible to assess the risk accurately through simulation.

External factors such as competitiveness and regulation affect testing. For example, many companies can offer a four-cylinder engine which pushes the limits of performance, reliability and durability. Targeted testing for specialised markets and applications is crucial. Market sector information for example, off-road or marine, also provides vital input for testing. Different sectors dictate different test methods against different contexts. Tests need to meet regulations and legislation for certification whilst ensuring that customer requirements continue to be met. With regulations revised in shorter

timescales and to tighter limits, companies cannot afford to run thousands of hours of physical testing for reliability and durability across each of the applications of a product. So there is a need for a revised testing strategy.

4.2. Decisions on types and modes of testing

A major decision for companies is the balance between component, subsystem level and system level testing. Component and subsystem level testing allows parallel testing and swift fault recognition. However, while a module might meet its own specifications, unpredictable interference and/or malfunction may appear when the whole system is assembled. This decision has influence on the number of tests, as well as on the time to perform a test.

Choosing between virtual and physical testing is a difficult decision for companies. Some engineers believe that a physical test will provide greater confidence in the test data; whereas others feel that there are inefficiencies in physical testing especially where repetition is needed for reliable data. A physical component test can deal with only limited variables and cannot always be comprehensive enough to include all the operating conditions. Furthermore, physical tests are conducted in a controlled environment and have limited capability to simulate the broad range of operating conditions.

On the other hand a virtual test through a computer aided engineering (CAE) model can handle a whole spectrum of variability across many interacting variables. This can prompt the identification and correction of design deficiencies and faults. However some of these computer models are still poorly supported [22]. There are risks in using a virtual model, for example if the service conditions are not quantified. It can be difficult to correlate virtual test data with the real world performance results, thus resulting in reduced confidence in virtual testing [12]. The CAE model can contain flaws which might be undetected until later stages in product development. In some cases CAE models can be complex in nature, so specialized knowledge or training is required, in addition necessary software can be expensive thus limiting accessibility [23, 24].

As both virtual and physical test have their own advantages and limitations, the literature suggests a combined approach of physical and virtual testing

might help to produce a focused test, increase reliability and minimize iteration [9, 12, 23-28].

The case study company may choose to carry out a physical test for the baseline product while using simulations for multiple variables relating to PD in specific use cases. Subsequently physical testing can validate simulations, if necessary. One engineer mentioned *“The baseline product definition is physically tested and that information is fairly adequate for simulation to run for multiple variables for longer time to find the optimum setup. Then a physical test is required to validate the simulated result”*. This model then can be used to predict a product’s behaviour. Karen et al. [29] state, and this was backed up by the validation manager in the case study company, that by feeding the physical testing results into simulations, a virtual test can be used to design an optimum system with the desired static and dynamic characteristics. During the interviews it was highlighted that a combined approach mixing physical and virtual testing methods reduces iterations and thereby the number of physical prototypes, saving time and cost. In a complex product physical tests might need to be focused towards the critical areas. A virtual test helps to set up the boundary conditions for a focused physical test.

4.3. Testing across the product development process

At different stages of the PD process, the roles of tests are considerably different. In earlier design stages, testing is more focused towards analysis and computer modeling and this can be used in combination with information available from similar or previous products. In later stages physical tests might be required for acceptance. The significance of different types of testing as well as the choice of physical and virtual testing is discussed in this section.

The case study company has a highly structured stage gate process for new product introduction (NPI) process (shown in the top row of Figure 1). It has eight stages starting from “Launch” to “Gateway 7”. We mapped the NPI process to a standard phase model of PD process with relevant testing activities. We consider from “Launch” to “Gateway 2” as early design stages, from “Gateway 3” to “Gateway 5” as detailed and production design. Changes can happen in any stages of these gateways. A schematic of the process is shown in Figure 1 adopted from [19], the

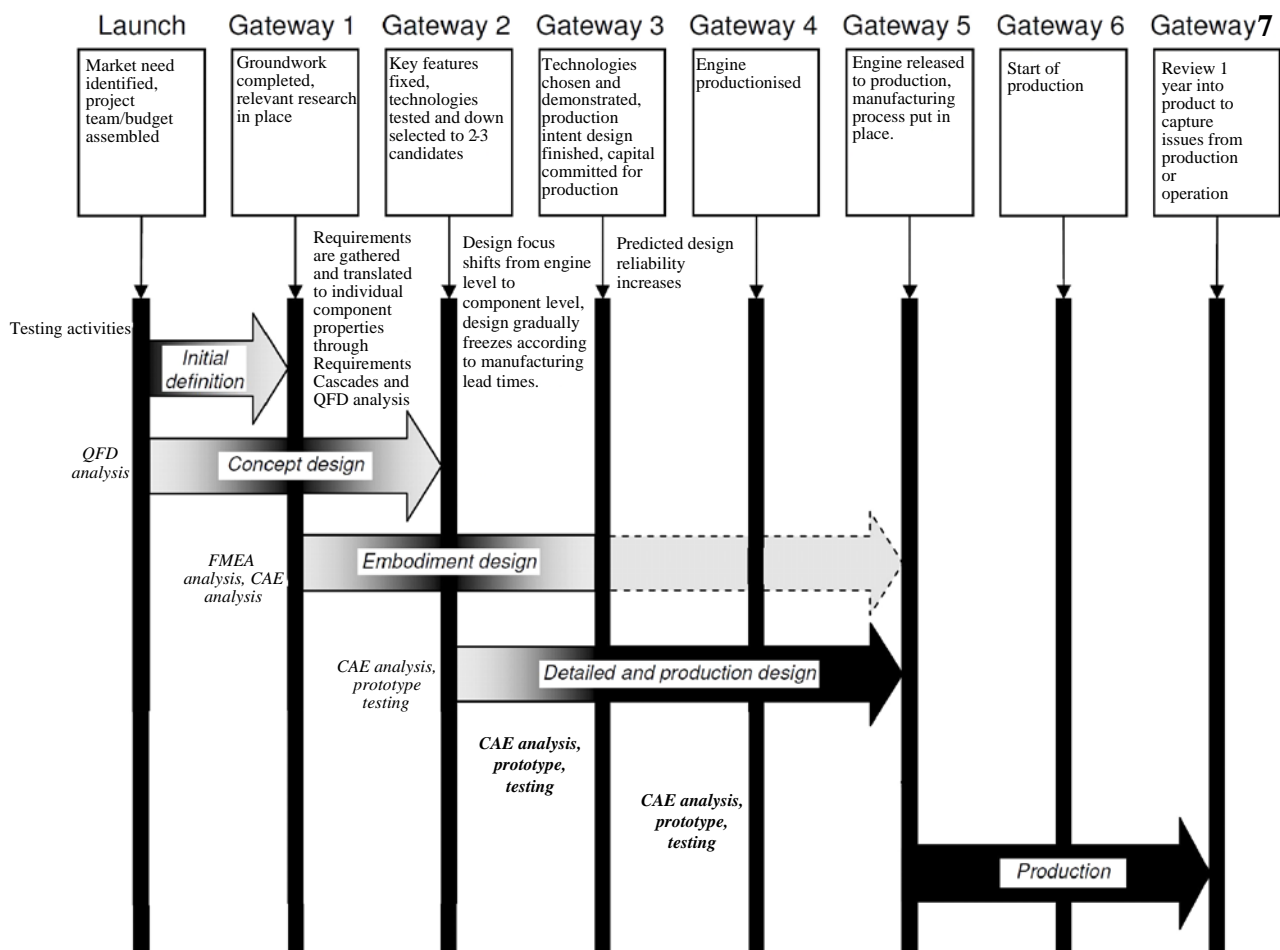


Figure 1 An outline of the company's NPI process (adopted from [19]).

output of a previous research project with same company.

Early design stage

In the early stage, testing consists mainly of concept verification. Concept specification, competitive product analysis and project justifications are done in this stage. Alternative concepts are generated, analyzed and evaluated. Early designs are analyzed as far as is practical to ensure the product's performance, reliability and durability against customer needs. Testing in this stage proves the feasibility of concepts [11].

The PD cycle time can be reduced if the quality measurement shifts towards early stages using upfront analysis at the conceptual stage [9, 30, 31], but early design phases require more coordination among design functions than other phases [30, 32]. Initially the PD process is driven by the requirements. The initial requirements are shaped in formal specifications and as the process progress are

often revised. A product must perfectly align with the specifications to be successful. Each specification should be measureable, testable or verifiable at each stages of PD process. Testing is considered as the primary way of measuring the performance of the product. The types and methods of testing should be stated and agreed on up front in the PD process.

At the early stages (between launch and Gateway 2) of the PD process, the company uses tools such as quality function development (QFD) to translate the customer requirements into the technical characteristics of product design which are used as input for the FMEA tools. Along with QFD, the previous product's health monitoring data and characteristics of product design are used as input for the Design FMEA, which focuses on identifying potential failures so that actions can be taken to prevent or minimize the effect of a failure. FMEA was introduced in the aerospace industry in the mid 1960s, with the focus on safety issues to prevent

failures and accidents. For incremental products, the company uses the FMEA of the previous product as a template for the new product's FMEA. FMEAs are used in different phases of PD process to indicate the priorities of actions to avoid failure of a product. The testing plan has emerged based on the analysis of FMEAs as well as expert judgment of engineers in the company. A flow diagram of the early validation and testing plan is shown in Figure 2. These plans try to balance the trade-off between prototyping costs and time and continue through the whole development process.

However this early planning mostly related to the physical testing, which will be performed towards the end of the PD process. Starting from a validated model for example FMEA or CAE analysis of an existing product helps the quality measurement (QM) through analysis of existing products to identify high risk and uncertain aspects of the design for future investigation, particularly physical testing.

Detailed and production design

At the detailed design stage, testing focuses on (i) requirement verification, (ii) performance analysis and (iii) reliability and durability checking. As the process reaches the detailed design stages, more physical objects are available and detailed virtual models are constructed of the new design. Detailed analysis of stress, strength, heat transfer and thermodynamics through virtual modelling are

performed in this stage. By the time proposals get to the Gateway 4 and Gateway 5, it is assumed that they will be achieving the required reliability. Both virtual and physical tests are options in this stage but engineers believe that the correct balance and intelligent integration is required for high fidelity testing and for minimizing the cost of physical testing. In this stage physical testing is driven by simulation testing. One engineer mentioned “*twenty hours of focused testing is better or equivalent then thousands hours of non-focused testing*”. By using simulation, boundary conditions are identified thus the physical testing becomes more focused and simplified. Simulation helps to focus on the conditions that are needed for physical testing and optimization of physical testing.

Design changes

Incremental design starts with changes to an existing design, which arise from new customer and legislative requirements. Problems with the emerging design during detail design can lead to urgent redesign [33], which propagates to connected components [34]. A change may be easier to incorporate in a virtual domain, whereas more effort would be required for the equivalent physical change [35]. Although all the processes are well defined, one engineer mentioned that “*the design change has a propagated effect which eradicates some of the testing, introduces more testing, questions whether we have tested in a right way, that's the thing that*

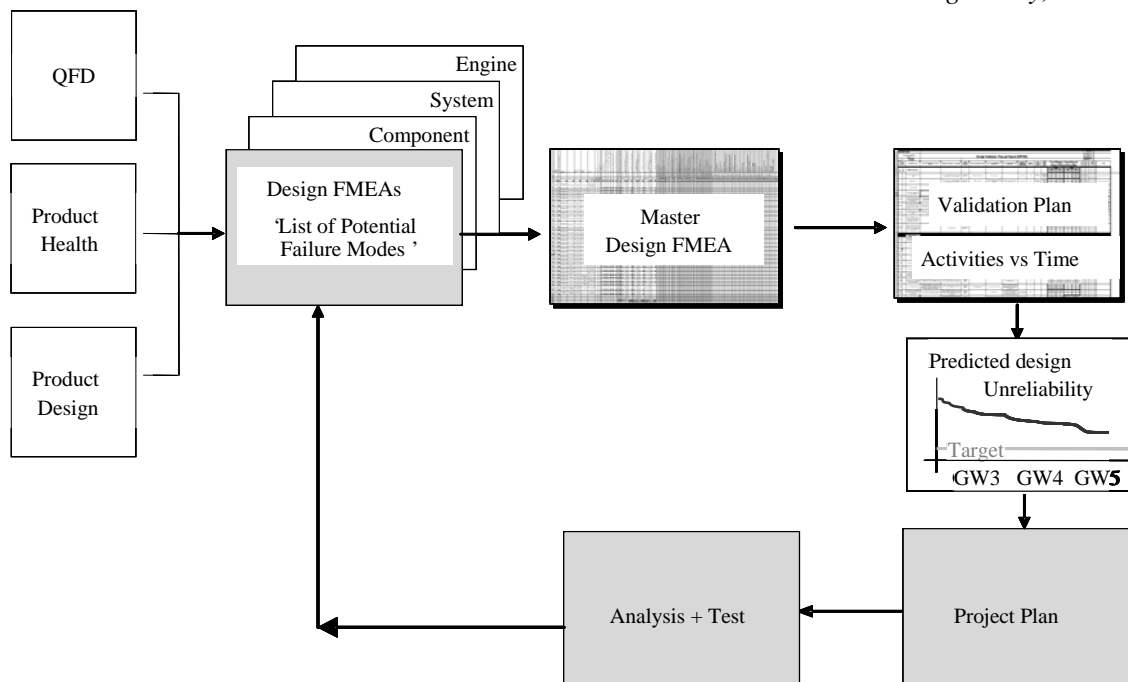


Figure 2 Company's Design FMEA process.

destabilized the process". A change of requirements from the customer has a big impact on the test plan. Thus it is important to capture, how the changes propagate, how the changes affect the testing plan, and how to reorganize the testing plan accordingly. Managing changes and especially their effect on testing is critical for an engineering company.

Figure 3 compares the current and desired distribution of testing effort in the company. The numbers in the figure based on rough estimates from the discussion with the engineers, but give an indication of the distribution at each stage of the PD process between analysis, virtual testing and physical testing. Figure 3(a) shows that analysis remains approximately the same throughout the process and as the process progresses the level of virtual testing increases. However most of the physical testing is done during the "Testing and Refinement" phase. Figure 3(b) shows the company's desired distribution, where virtual testing and analysis should minimize physical testing. Physical testing is started as soon as the prototypes are available.

It has been realized that product design and testing need to be closely integrated. Levardy et al. [11] suggested that the best time to start a test is immediately after the design task is delivered. The testing domain needs the information from the design department to perform required tests but equally test outcomes must feedback to the design department in real time to avoid unnecessary delay. The challenge for the company is to achieve close collaboration between the design and testing domains to encourage the direct and immediate exchange of information.

5. DEPENDENCIES AND STRUCTURE MATRICES

In this section the dependencies and interrelations between tests are discussed. In section 5.1, the logical reasons behind identifying dependencies are discussed. To effectively visualize the dependencies between testing and design domain, a dependency model is proposed in section 5.2. In section 5.3, the ways of identifying the change propagation is mentioned.

5.1. Dependencies between tests

The interrelations between the tests and learning from the tests are recognized as critical in the case study for planning testing activities. Particular attention to dependence and information flow between tests is addressed in the following section.

Several key factors in planning tests were identified from the interviews: (1) testing should be considered as an integral part of the PD process, (2) a combined approach of virtual and physical testing is required for effective testing to balance the time and cost, (3) engineering changes must be accommodated within the test planning process and there must be an effective strategy to cope up with these changes. Planning tests should take into account that: (i) a change in one test might affect other tests, for example one test might render another redundant or invalid, (ii) changes to a single component will affect testing plans, so understanding the working links of components, subsystems and systems helps identify the appropriateness of a test and (iii) a change to one

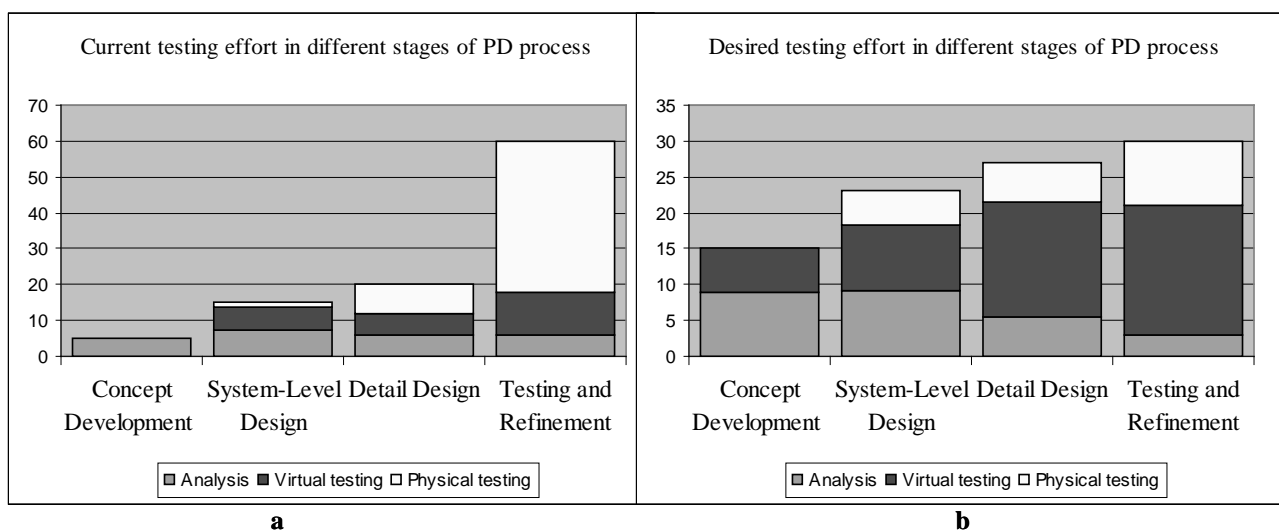


Figure 3 Current and desired testing effort distribution of testing in the PD process.

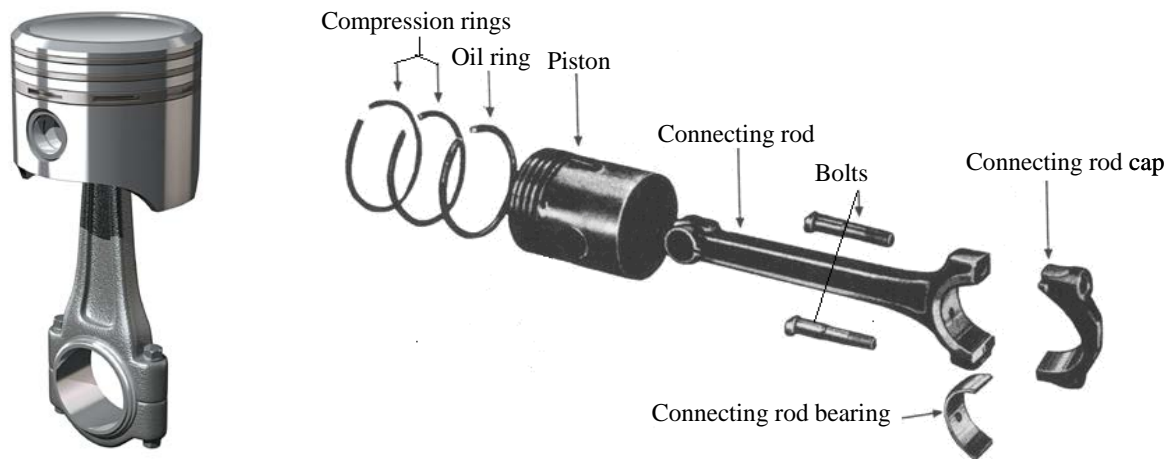


Figure 4Decomposition of piston and connecting rod

Table 1 The basis of dependency for DSM

Component-Component (Top left Matrix)	Test – Test (Bottom right Matrix)	Test to component (bottom left Matrix)	Component to Test (Top right Matrix)
(i) Test result on one component is required to perform a test on another (ii) Components are functionally dependent (iii) Components are architecturally dependent	Component level tests need to be performed before system level tests. The information of one test is used for another test.	The requirements, parameters, procedures of a test need to change because the component under test has changed.	Usually doesn't happen (A component doesn't change because a test has changed).

component of the product may result in changes to other components or parts and associated tests.

Loch et al. [8] identified how optimal testing strategies are influenced by three important factors: cost, learning between tests and feedback time to design domain. Hoppe [11] suggested that the selection of test activities should be based on the maturity of information required to perform the test, which might come from other activities. These factors might also have significant influence in configuring the tests sequentially or in parallel [1, 8].

5.2. Dependency model

The insights from the case study have been used to develop a Design/Dependency Structure Matrix approach. The Dependency Structure Matrix (DSM) is an established method for capturing the sequence and complex interaction of design tasks [7] and was used to capture the dependencies and address the illustrated issues. We focused on a small part of the engine i.e. piston and connecting rod (in Figure 4) to illustrate our approach. **Table 1** identifies the types of dependency we considered for DSM modeling.

Figure 5 shows a DSM of the relationships among the components and dependencies between the tests. A static component based DSM (CDSM) is being used to capture the interactions between the components of the product (top left matrix). The spatial and functional relations between piston, compression rings, connecting rod etc. are modelled in this matrix. These are spatial and functional relations with some exceptions. For example, the oil ring may not have any spatial relation with the connecting rod bearing but oil passes through the bearing to the connecting rod to the oil ring to lubricate the piston and this process establishes a connection between oil ring and connecting rod bearing.

As a test is performed on a component, the bottom left domain-mapping matrix (DMM) shows the relationship between tests and components of the product. It presents which tests are performed on which components and can bring out interesting issues. For example a performance test is a sub-system level test as it is performed on piston, compression rings, and oil ring, which are spatially connected. However, some tests for example wear

tests, are performed on both compression ring and connecting rod bearing that are not spatially connected. Therefore questions arise whether these tests are different and performed separately on compression ring and connecting rod bearing, or should be if a single test to measure both types of wear at the same time.

A further activity based DSM (ADSM) has been used to capture the sequences and dependencies between different tests (bottom right matrix). These relations are based on the tests as performed during the PD process. Component level tests are done before the system level tests. For example, blow by tests are performed on compression rings before it goes to system level performance tests installed on an engine. Again some of the tests at any level might be performed in a single test although the reason behind each separate component test is different. For example, heat expansion tests and temperature measurement tests might be performed at a same time. There are also tests that need to be performed earlier than others because the observation of one test is used as the input for another test. For example the sequence of tests on a piston will be heat expansion test, stress test, strain test and finally the performance

test.

The matrix in the top right corner is not modeled because we have not yet collected data on “design for testability”.

5.3. Changes

Comparing these DSMs offers the potential to examine the consequences of changing a test or a component. Change propagation through the product architecture and its influence on the testing plan can also be captured by comparing these two DSMs. The ADSM can help to capture the relationship and dependencies between virtual and physical testing through the course of the design process. These DSMs also offer the potential to examine the possibility of replacing a physical test with virtual test with a specified confidence level. These relations provide essential insights for developing a tool for effective test planning.

For a next generation product, the learning from the previous product forms the basis of a testing plan for new product. The confidence level of some tests will have increased over time. The engineers are confident and can decide whether a virtual testing is

CDSM	1	2	3	4	5	6	7		a	b	c	d	e	f	g	h	i	j
1. Piston		X	X	X														
2. Compression rings	X																	
3. Oil ring	X				X													
4. Connecting rod	X				X	X	X											
5. Conn. rod bearing			X	X		X												
6. Connecting rod cap				X	X		X											
7. Bolts				X		X												
DMM									ADSM									
a. Stress analysis	X											X	X				X	
b. Strength test of piston head	X																X	
c. Heat-expansion measurement	X								X				X			X		
d. Performance	X	X	X											X	X			X
e. Temperature measurement	X								X		X							
f. Wearing test		X			X							X						
g. Blow by test		X																
h. Fatigue resistance					X				X	X			X					
i. Load carrying capacity					X				X	X								
j. Vibration test				X					X									

Figure 5 A DSM of test and component

adequate in that level. This shifts the testing strategy from physical to virtual and reduces iteration. As a company designing and manufacturing a mature product, engineers at the case study company might be able to judge each test and place a numerical value according to their confidence. By comparing the values, decisions can be taken on switching or combining the virtual and physical testing. A numerical ADSM model with associated values in each test will be useful to plan the testing process. This is the next step of this research and is currently being investigated by the authors.

6. CONCLUSION

This research draws several conclusions based on the case study and subsequent analysis:

1. This research highlights the importance of studying the testing process as an integral part of the product development process. To integrate testing throughout the PD process, upfront analysis of QFD and FMEA can play a vital role in linking design considerations with the testing plan. Early planning around testing might help effective resource allocation and shift the quality management upfront. Re-planning the testing activities according to any design changes as the product progress is equally important for optimum testing results. A combined approach of virtual and physical testing is required for effective implementation of testing activities, especially replacing expensive physical testing and providing better overall confidence in testing results.

2. Identifying the types, modes, dependencies and interrelations between tests are vital for effective planning of the testing process. The proposed DSM model captures the dependencies between tests. The proposed model offers the potential to restructure the tests that eventually will assist to organize the testing activities along the PD process. At the same time the connectivity network between the tests and the components will help to visualize how each element of the testing effort contributes to overall requirements.

3. Responding to engineering changes during product development is particularly dependent on understanding how testing processes are integrated with design. This model will be also useful for prompt identification of propagating flow of any change in one test or a component in the system.

Further work will extend validation of these models in an industrial context, including the original case

study company. In particular, contexts with products at different scale, complexity and maturity will be compared. Further work will also include a detailed analysis of the proposed DSM model to identify the clusters of tests or where separating coupled tests is required for resource effective planning.

As testing is a costly process, the results highlight new ways to use scarce resources effectively to deliver quality products while maintaining competitive advantage in meeting a rolling programme of regulatory constraints. Integrating physical and virtual testing is more than a process optimization of time and cost because it contributes to recasting the design process itself as a response to change, both against new customer requirements and contingently in responding to design changes which occur during product development.

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